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# Solitary re-entrant superconductivity in asymmetrical FSF structures

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ABSTRACT

Solving the boundary value problem for the Eilenberger function, the superconducting and magnetic states of asymmetric ferromagnet–superconductor–ferromagnet ($F_1SF_2$) nanostructures are investigated. The dependences of critical temperature on an exchange field of the F metal, electronic correlations in the S and F metals, and thicknesses of layers F and S are derived. It is shown that the possibility of the Larkin–Ovchinnikov–Fulde–Ferrell (LOFF) state observation is especially increased in the asymmetrical trilayers $F_1SF_2$ for which solitary re-entrant superconductivity is predicted. The possibility of solitary re-entrant superconductivity for asymmetrical trilayers $F_1SF_2$ in the dirty limit is also shown.



## 1. Introduction

Superconductivity arises in the artificial layered ferromagnet–superconductor (FS) nanostructures due to a proximity effect [1]. As a rule, superconductivity occurs for $d_f \ll d_s$, where $d_{f(s)}$ is the F(S) layer thickness. The typical case is the layered Gd/Nb and Fe/V structures (see reviews [2–7] and references therein), where superconductivity is a superposition of the Bardeen–Cooper–Schrieffer (BCS) pairing with zero total momentum in the S layers and the Larkin–Ovchinnikov–Fulde–Ferrell (LOFF) pairing [8,9] with nonzero three-dimensional coherent momentum in the F layers. However, the 3D superconductivity in the Gd–La superlattice not only exists for $d_f > d_s$, but it appears at $T_c$ equal to the critical temperature of a bulk lanthanum sample $T_{cs}$ [10,11].

This surprising behavior was explained in the recent papers [12,13] based on a solution of the boundary value problem for the Eilenberger function for the FS bilayer and symmetric FSF trilayer. This three-dimensional theory of the proximity effect takes into account spatial variations of the Eilenberger function not only across the F and S layers, but also along the F–S contact. In addition, our theory takes into account the magnitude and sign of the electron–electron interaction in a ferromagnet, which is unreasonably disregarded in previous theories [2–5]. In the present paper we use this approach to explore the superconducting and magnetic states of asymmetric ferromagnet–superconductor–ferromagnet ($F_1SF_2$) nanostructure and to look for the solitary re-entrant superconductivity. Besides the prediction in the pure limit we use the standard Usadel equations [2,4] for estimation of this effect in the dirty limit.

Note that the common re-entrant superconductivity for the FS systems was theoretically predicted in [14]. Later it was observed experimentally [15].

## 2. Appearance of re-entrant superconductivity

### 2.1. Clean limit

Using the formalism developed in works [12,13] for symmetrical FSF structures we can easily obtain generalization for the asymmetrical case (see Fig. 1). For simplicity we will use the Cooper limit when the mutual effect of $F_1$, S, and $F_2$ metals is particularly strong due to the collectivization of electron correlations and the paramagnetic effect of the exchange field $I$. In this limit the layer thicknesses are small, $d_{s(f)} \ll \xi_{s(f)}$, $a_f$ ($\xi_{s(f)}$ is coherence length, and $a_f = v_f/2I$ is the spin stiffness length).

In the present work we consider a simplified version of the theory—the contact of metals with the same electronic structure (their Fermi velocities are equal, $v_s = v_f = v$) excluding exchange field (which equals zero in the S metal) and electron–electron interactions (whose constants can be different for the S and F metals, i.e. $\lambda_s \neq \lambda_f$). We also suppose that internal boundaries have ideal transparency [13]. The equation for the critical temperature $T_c$ becomes

$$\ln\frac{T_c}{T_{cs}} = \frac{(c_{f1}+c_{f2})(\lambda_f-\lambda_s)}{\lambda_s[c_s\lambda_s+(c_{f1}+c_{f2})\lambda_f]} + \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\left\langle \Psi\left(\frac{1}{2}+\frac{i\Gamma}{4\pi T_c}\right)\right\rangle; \quad \Gamma = 2I(c_{f1}-c_{f2}) + \mathbf{q}\mathbf{v}_\perp. \quad (1)$$

Here $T_{cs}$ is the critical temperature of the isolated S layer, $\Gamma$ is the pair-breaking factor, and $\Psi(x)$ is the digamma function. $\langle \cdots \rangle$

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